NTP Development Activities at the NASA Marshall Space Flight Center - 2006 Accomplishments

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Abstract. In 2005-06, the Prometheus program funded a number of tasks at the NASA-Marshall Space Flight Center (MSFC) to support development of a NTP system for future manned exploration missions.
These tasks include the following:

- NTP DDT&E Planning
- NTP Mission & Systems Analysis / Stage Concepts & Engine Reqts
- NTP Engine System Trade Space Analysis and Studies
- NTP Engine Ground Test Facility Assessment
- Non-Nuclear Environmental Simulator (NTREES)
- Non-Nuclear Materials Fabrication & Evaluation
- Multi-Physics TCA Modeling

This presentation is a overview of these tasks and their accomplishments

NTP Development Activities

At the NASA Marshall Space Flight Center

- 2006 Accomplishments -

NTP Development Tasks

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NTP Design, Development, Test & Evaluation (DDT&E) Planning

Task Manager: Rick Ballard

NASA / MSFC / ER24

NTP DDT&E Planning

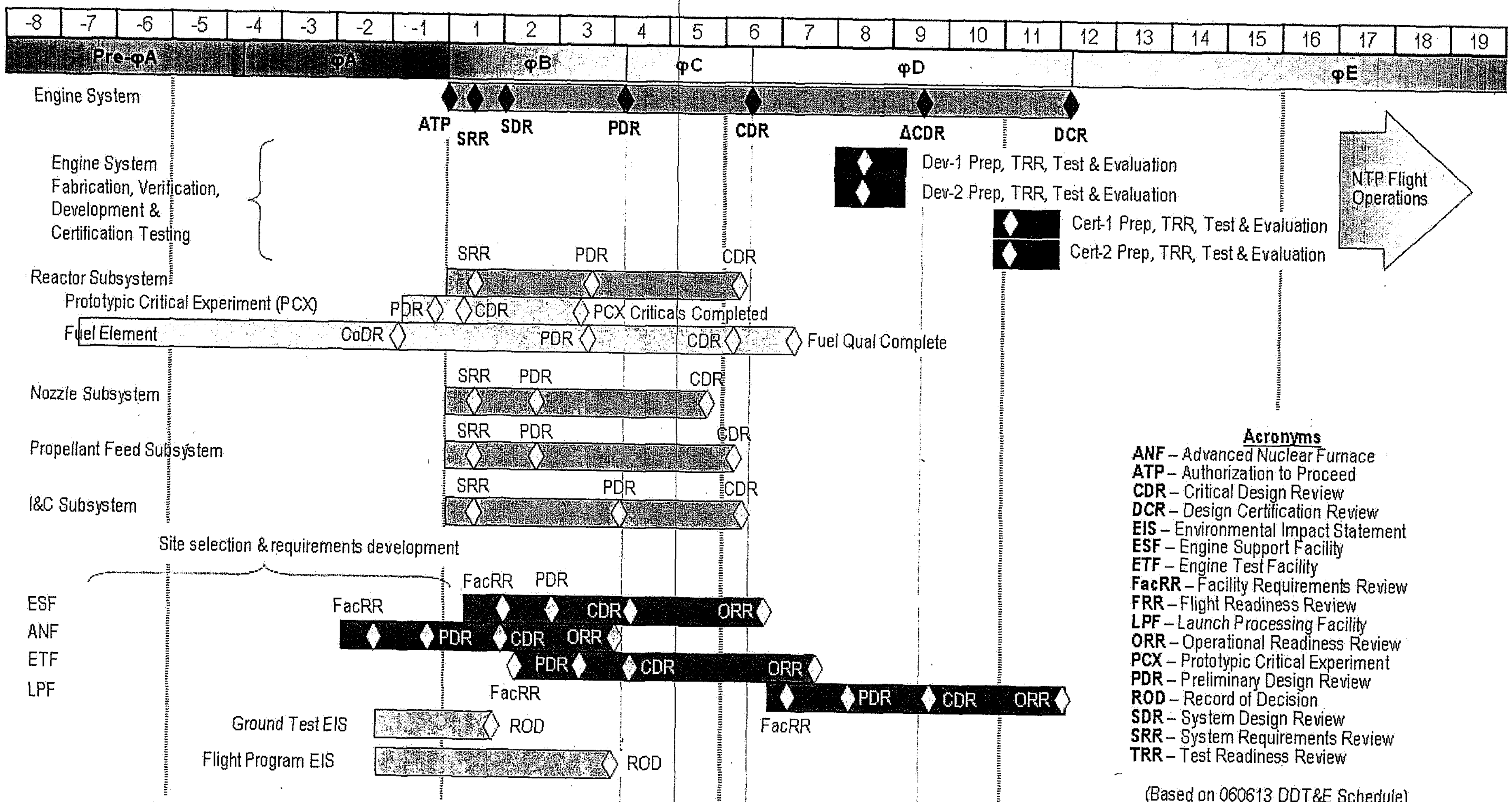
Description

- Need, Issue, and/or Opportunity
  - Develop initial DDT&E planning as foundation for NTP system development. Develop infrastructure requirements and activities for nuclear and non-nuclear development of system and subsystems.
  - Recover and archive legacy documents from previous NTP activities to support future efforts
- Scope
  - Initial development planning through prototype NTR development and accomplishment of first flight demonstration.
- Objectives
  - Identify critical programmatic sensitivities, establish communications with NTP development elements (NASA, DoE) and develop DDT&E plan specific to NTP development.

Approach

- Partners
  - DoE/LANL support has been established
- Contracts/Procurements
  - P&W-R – System engineering approach
  - Aerojet – NERVA document recovery
- Facilities
  - None required
- Options
  - Potential for expanding scope to include program planning, acquisition strategy development, requirements development, systems analyses and trades, and systems engineering processes and tools development.

NTP DDT&E Flow



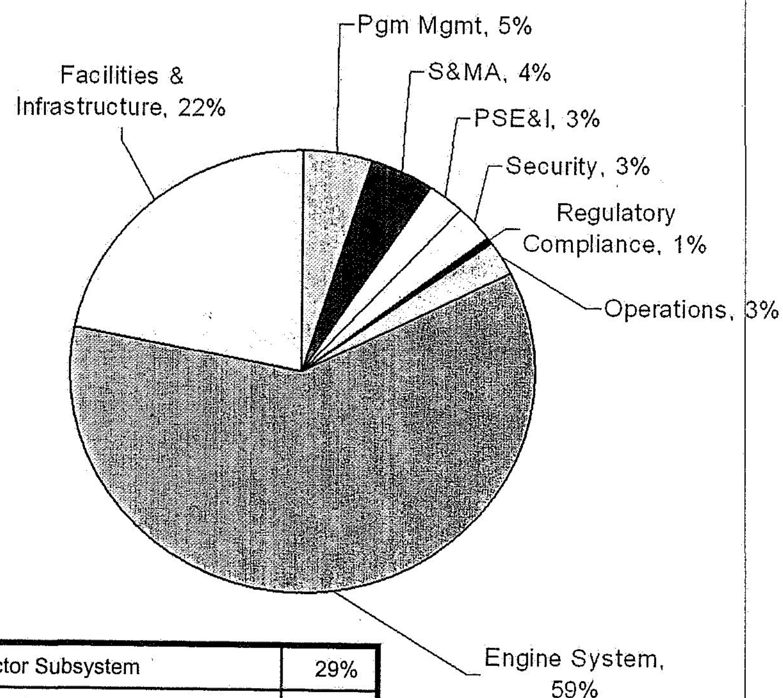
Acronyms

ANF – Advanced Nuclear Furnace
ATP – Authorization to Proceed
CDR – Critical Design Review
DCR – Design Certification Review
EIS – Environmental Impact Statement
ESF – Engine Support Facility
ETF – Engine Test Facility
FacRR – Facility Requirements Review
FRR – Flight Readiness Review
LPF – Launch Processing Facility
ORR – Operational Readiness Review
PCX – Prototypic Critical Experiment
PDR – Preliminary Design Review
ROD – Record of Decision
SDR – System Design Review
SRR – System Requirements Review
TRR – Test Readiness Review

(Based on 060613 DDT&E Schedule)

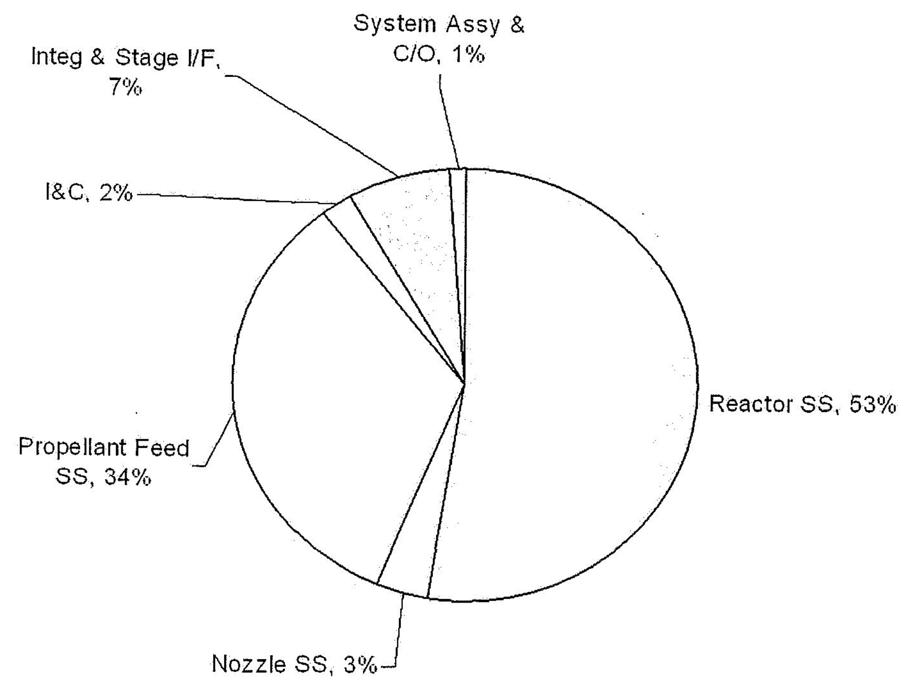
NTP DDT&E Resource Fractions

DDT&E Cost by WBS



Reactor Subsystem	29%
Nozzle Subsystem	~2%
Propellant Feed Subsystem	16%
Instr. & Controls	~3%
Integ. & Stage I/F Hdwe.	3%
Test & Evaluation (system)	5%
GSE	~1%

NTP Engine Per Unit Cost



NTP Archive Accomplishments to Date

- Recovered hardcopy documents and files for OCR scanning into PDF format and archiving
- Added high technical content movies from KIWI, ROVER, PEWEE, PHOEBUS and SNAP programs.
- Compiled integrated master index with hyperlinks to a web-based archive
- Loaded to server and linked to master index: ~1100 files (7.0 GB, was ~100 files one year ago)
  - Gerrish/Federal Records Center
  - Marshall Repository's paper files
  - NERVA program documents from Aerojet and Westinghouse
  - Redstone Scientific Information Center and NASA's Aeronautics and Space Database (CASI)
  - SNTP material from Sandia National Laboratory
  - Other
- Generating DVD library of all legacy documents as well as MSFC NTP task products (17.7 GB)

NTP Mission & Systems Analysis / Stage Concepts & Engine Requirements

Task Manager: Jack Mulqueen

NASA / MSFC / EI63

Description

- The Mission and Systems Analysis addresses the need to identify potential Nuclear Thermal Propulsion engine requirements for human Mars exploration missions.
- Scope – The NTP MSA study defined the range of potential NTP engine requirements by defining four point-of departure Mars transportation vehicles representing the potentially most demanding requirements and the least demanding requirements for a nuclear propulsion system.
- Objective - The objective of this task was to derive NTP requirements for human Mars exploration missions based on mission and system analyses, as well as design sensitivity trades of potential Mars transportation architectures consistent with the National Vision for Exploration

Approach – Phase 1 Subtasks

- **NTP Mars Vehicle Design Concept Analysis**
  Perform parametric trade and sensitivity studies of Mars NTP vehicle design concepts sized for the 2025-2035 Mars mission opportunities to identify the best NTP stage and engine design options based on a comprehensive set of figures of merit.
  - **Develop PARSEC NTP vehicle point of departure design concepts**
    - Case 1: All Propulsive NTP Vehicle - All-Up Mission
    - Case 2: All Propulsive NTP Vehicle - Split Mission
    - Case 3: NTP/Aerocapture/Chemical Propulsion Vehicle - All-Up Mission
    - Case 4: NTP/Aerocapture/Chemical Propulsion Vehicle - Split Mission
  - **Figure of Merit Analysis**
    - Safety, Reliability and Operations
    - Performance and Mission Objectives
    - Affordability (Cost)
  - **NTP vehicle performance sensitivity trades**
    - Multiple vs. Single Engine
    - Engine Thrust-to-Weight
    - Engine Nozzle Area Ratio
    - Engine Thrust Level
    - Engine Specific Impulse
    - Particle Bed Reactor vs. Solid Core Reactor

Approach – Phase 2 Subtasks

- **NTP Mars Vehicle Design Concept Analysis**
  Define NTP requirements and a representative Mars NTP vehicle design concepts sized for the 2025-2035 Mars mission opportunities for the ESAS Mars mission architecture.
  - NTP System Analysis of the ESMD reference mission
    - Mission Analysis
    - NTP point-of-departure design concept
  - NTP Vehicle and Engine Sensitivity Analysis
    - Integrated vehicle/engine shielding analysis
    - Single vs. multiple engines
    - NTP Engine Parameter Sensitivities
  - NTP Engine Requirements for the ESMD Reference Mission
    - Prismatic graphite fuel (NERVA) NTP
    - Advanced NTP
  - Phase 2 Final Report

Approach – Task Collaboration

NTP for Exploration Task # 6

Mission and Systems Analysis and Requirements Support

- Sensitivity
- Trades
- FOM Analysis

Mission Analysis

- Mission Year
- Trajectory

Vehicle Systems Analysis

- Payloads
- Configuration
- Operations

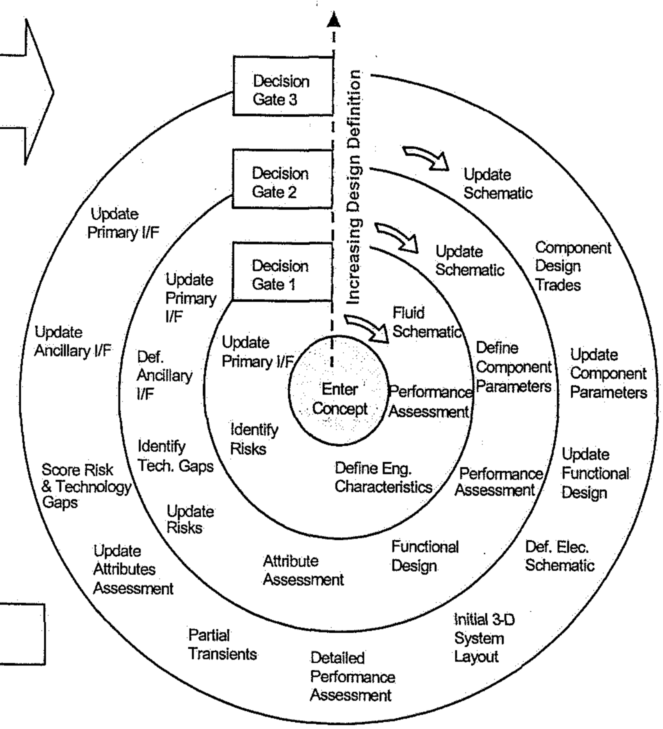
Engine Requirements

- Thrust
- Isp
- # of Burns
- Burn Duration

NTP for Exploration Task # 7

Nuclear Thermal Propulsion Engine System Study

Engine Concept & Model Development Cycle



Accomplishments

- Electronic Searchable Index of Mars NTP Vehicle Studies 1967-2005
  - 83 Documents
- Completed Mars Mission Trajectory Analysis
  - Optimized Short-Stay and Long Stay Trajectories for 2025-2035
- Developed Mars NTP Vehicle Design Concepts
  - Phase 1 : Short Stay Missions
  - Phase 2 : Long Stay Missions (ESAS Reference Architecture)
- Sized NTP Engine Concepts for Human Mars Missions
  - Phase 1 : 250 klb – 100 klb Thrust Engines
  - Phase 2 : 150 klb – 25 klb Thrust Engines
- Performed NTP Engine and Radiation Shield Trade Studies
- Defined Initial NTP Engine Requirements For Human Mars Missions

NTP Engine System Trade Space Analysis and Studies

Task Manager: Karl Nelson

NASA / MSFC / ER21

Description

- Needs
  - The ability to quickly and accurately design and analyze NTP engine system concepts
  - System and component requirements for potential concepts to guide future work

- Objectives
  - Develop and validate a design/analysis process and the capabilities needed to evaluate NTP engine system concepts
  - Determine system and component level engine requirements using conceptual level designs
  - Identify risk and gap areas of engine system and component designs

Approach

- Leverage a proven trade study design approach used for chemical rocket engines
  - Utilize recent NTP Mars mission studies for top level requirements
  - Select engine concepts/cycles of interest
  - Identify Figures of Merit (FOMs) and develop process for scoring concepts
  - Perform analyses, trades, and parametrics on NTP concepts with system/component models to determine sensitivities and requirements
  - Generate database (spreadsheets) with comprehensive set of system and component attributes for collaboration among team
  - Evaluate concepts based on FOMs
- Develop an overall NTP engine system design/analysis tool with integrated component models and reactor model
- Generate and integrate an engine system reliability model
- Develop 3-D CAD model of POD engine design
- Include DoE and industry partnering to obtain expertise in specific areas

Approach (cont'd)

- Scope
  - Begin with preliminary modeling and evaluation of "NERVA Derived" engine systems
  - Continue with detailed modeling and evaluation of "NERVA Derived" engine systems
  - Follow with detailed modeling and evaluation of "CERMET Prismatic" systems
  - Continue process for systems with other reactor types as requested

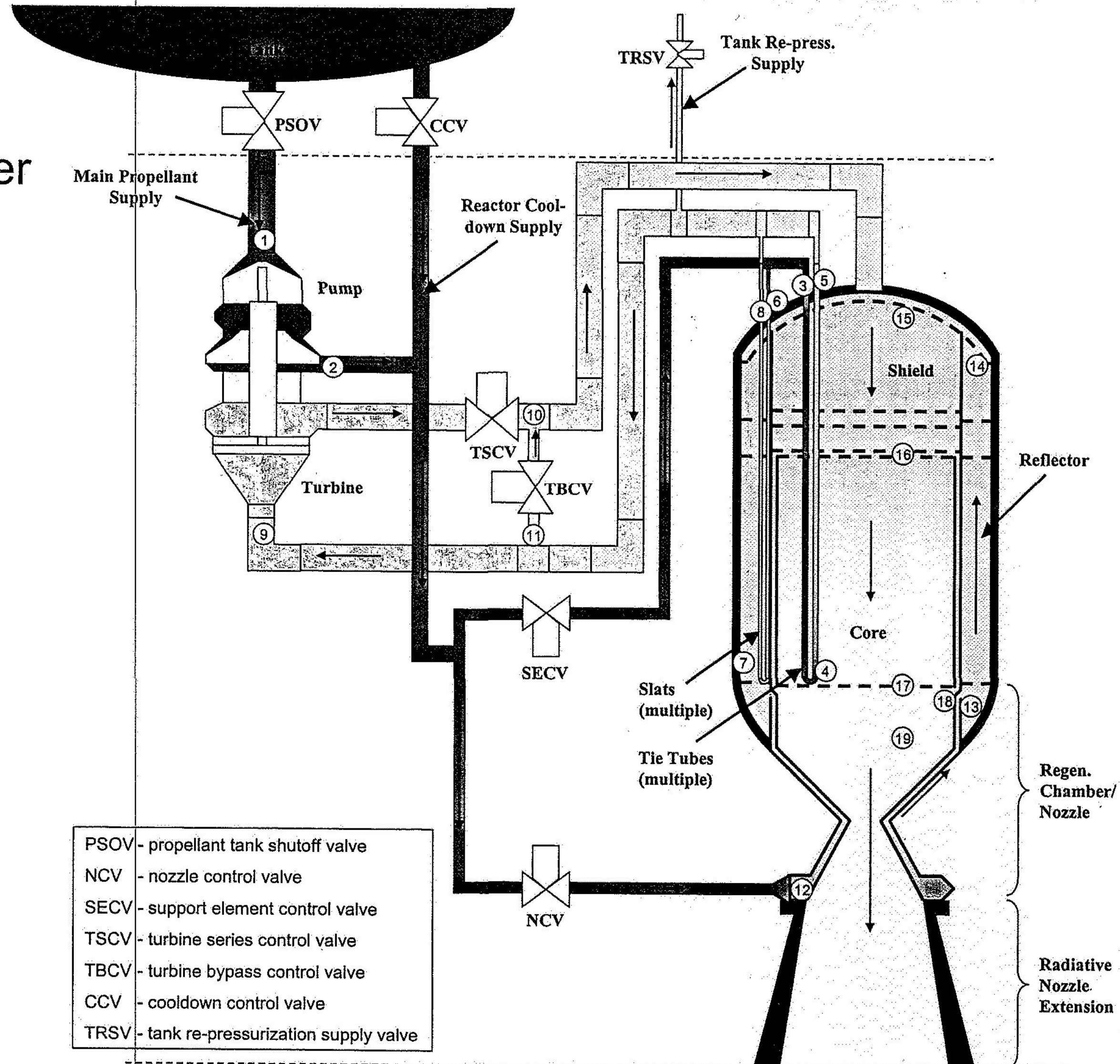
- Primary Deliverables
  - NTP engine system design/analysis tool with integrated non-nuclear and detailed reactor component models for performance, sizing, and reliability
  - Engine Specification Documents with engine conceptual designs and requirements

Accomplishments

- Generated engine system trade tree
- Defined top-level requirements and trade space based on recent NTP Mars missions
- Identified FOMs - weight (T/W), Isp, envelope, reliability, risks, and cost
- Selected cycles of interest based on a Point of Departure (POD) "NERVA Derived" engine design and created schematics for each cycle
- Completed preliminary NTP design/analysis tool with integrated component models and reactor model
- Ran cases for "NERVA Derived" baseline cases at thrust levels from 15 to 250 klbf
- Populated spreadsheets for each case for further evaluation by team
- Performed additional system trades (P_c, ε) on "NERVA Derived" cases
- Completed radiation effects assessment for component materials
- Completed NTR Fuel Temperature Sensitivity Study
- Performed two multi-pump vs. multi-reactor reliability study (50 and 75 klbf)
- Completed, documented, and integrated external shield model from SAIC
- Creating 3-D CAD model of POD engine including external plumbing
- Generating component Failure Modes and Effects Analyses (FMEAs) and physics based scaling of failure events for system reliability model
- Generating detailed "NERVA Derived" reactor model with LANL

Point of Departure (POD) Engine Design

- "NERVA Derived" Expander (Topping) Cycle – NERVA Small Engine design
- Solid core, prismatic, graphitic fuel elements
- Hydrogen cooled tie tube support elements
- Regeneratively cooled chamber and nozzle
- Radiatively cooled nozzle extension

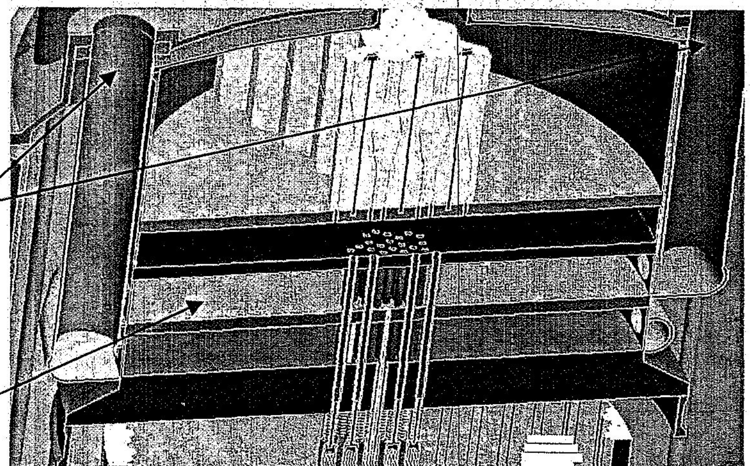


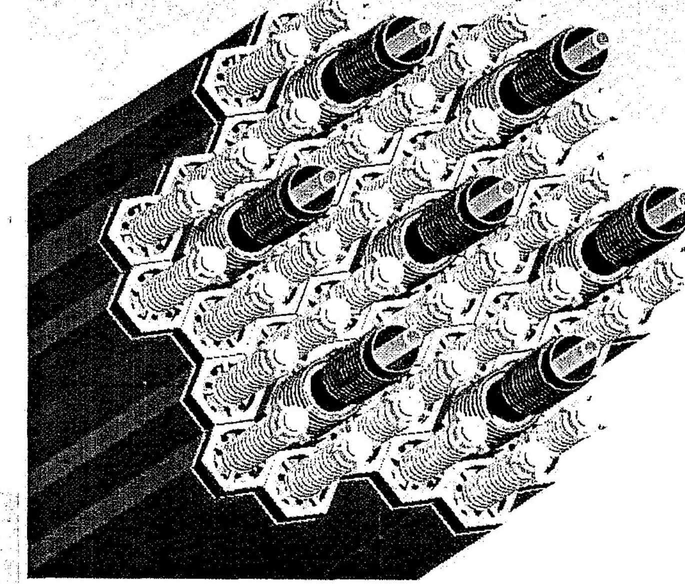
POD Engine 3-D CAD Model

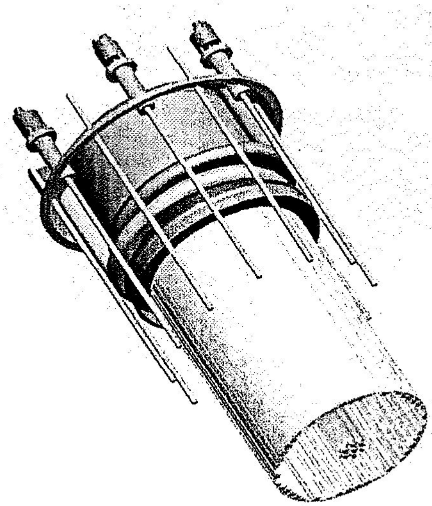
75klbf "NERVA Derived" Full-Flow (Expander) Cycle Engine

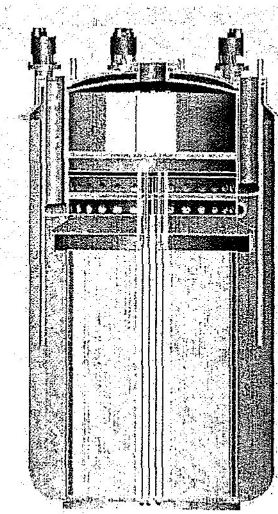
Single tie tube supply and returns replaces manifolds with multi-supply/ return lines from NERVA

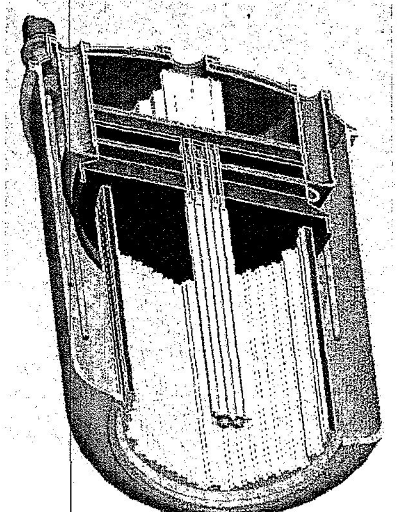
New down-comer tie tube supply manifold replaces individual tube supply from NERVA

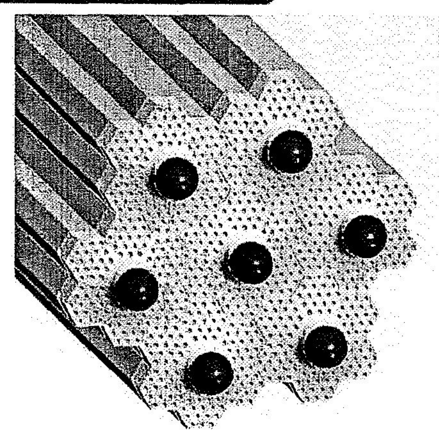












NTP Ground Test Facility Assessment

Task Manager: Jim French

ARES Corporation

Description

- Need
  - Assessments Needed of Options for Full-Scale Engine Level Testing
  - Costs and Schedule to Modify Existing or Build New Facilities is Unknown and a Significant Program Uncertainty/Risk
- Scope
  - Focused on Full-Scale Engine Level Testing and Supporting Infrastructure
- Objectives
  - Understand Issues and Process to Define and Develop a NTP Ground Test Facility
- ARES Corporation Providing Supporting Analysis for Facility Concept Assessment
  - Local Huntsville Office Leading Study
  - Support from Richland, WA (Hanford) Office
- Deliverables
  - Ground Test Approach and Site Assessment Report
  - Ground Test Facility Concept Definition
  - Executive Briefing for Program 12-month Review
  - Summary In-house Briefing

Accomplishments

- Defined Point-of-Departure Engine Characteristics and Testing Requirements
- Defined Process for Site and Test Approach Assessment
  - Defined Ground Rules
  - Identified Options
  - Conducted Site visits to INL and AEDC for Facility Information
  - Created Scoring Process
  - Conducted In-House Options Scoring Process
  - Created Hybrid Assessment Using ROM Cost Scores to Augment Experts' Scores
- Conducted Cost and Schedule Sensitivity Analysis
  - Initially for Eight Site and Test Approach Options
  - Updated for Two "Defined" Concepts
- Developed "Definitions" of Two GTF Concepts to Drive Out Issues
- Made Risk Assessment and Recommendations for Risks Mitigation
- Delivered Study Results in Two Reports (March & May, 2006)

NTP GTF Site Trade Tree

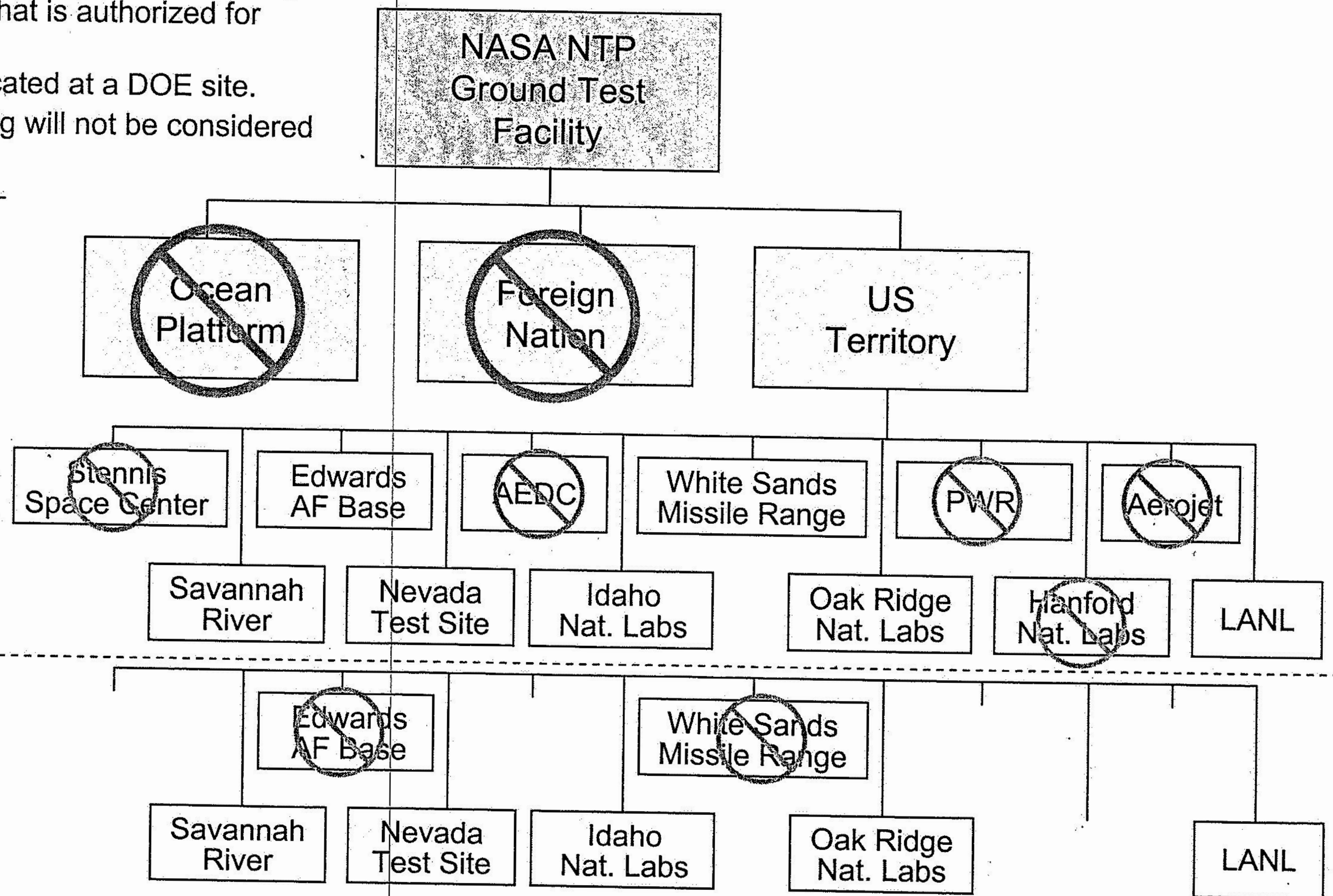
GROUND RULES

1. The NTP GTF will be located within the US.
2. The NTP GTF will be located within an existing US Government site that is authorized for Category I SNM.
3. The NTP GTF will be located at a DOE site.
4. Open Air Exhaust Testing will not be considered for the NTP GTF.

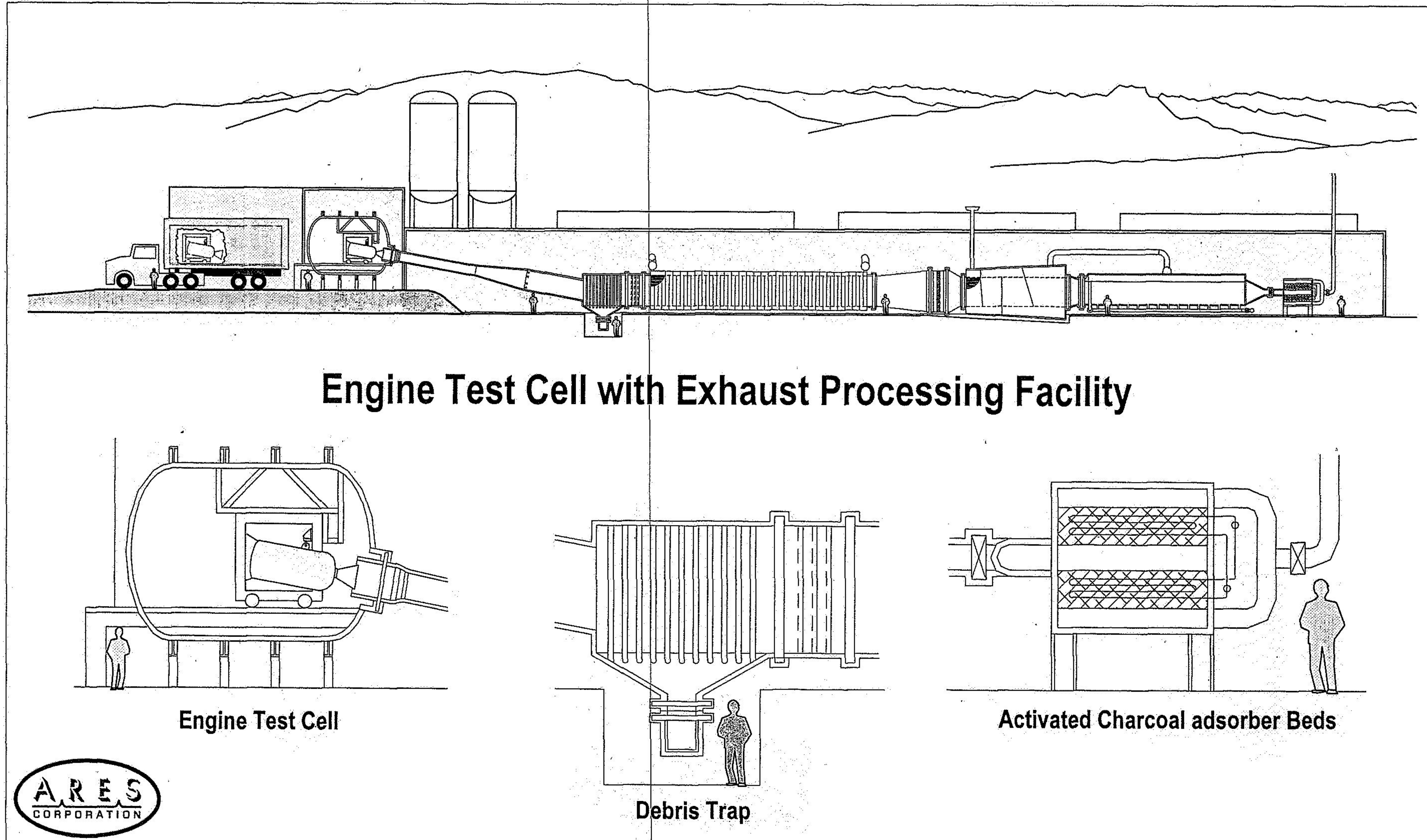
Geographic Location
(Ground Rule 1 Applies)

Govm't Cat 1 Site
(Ground Rule 2 Applies)

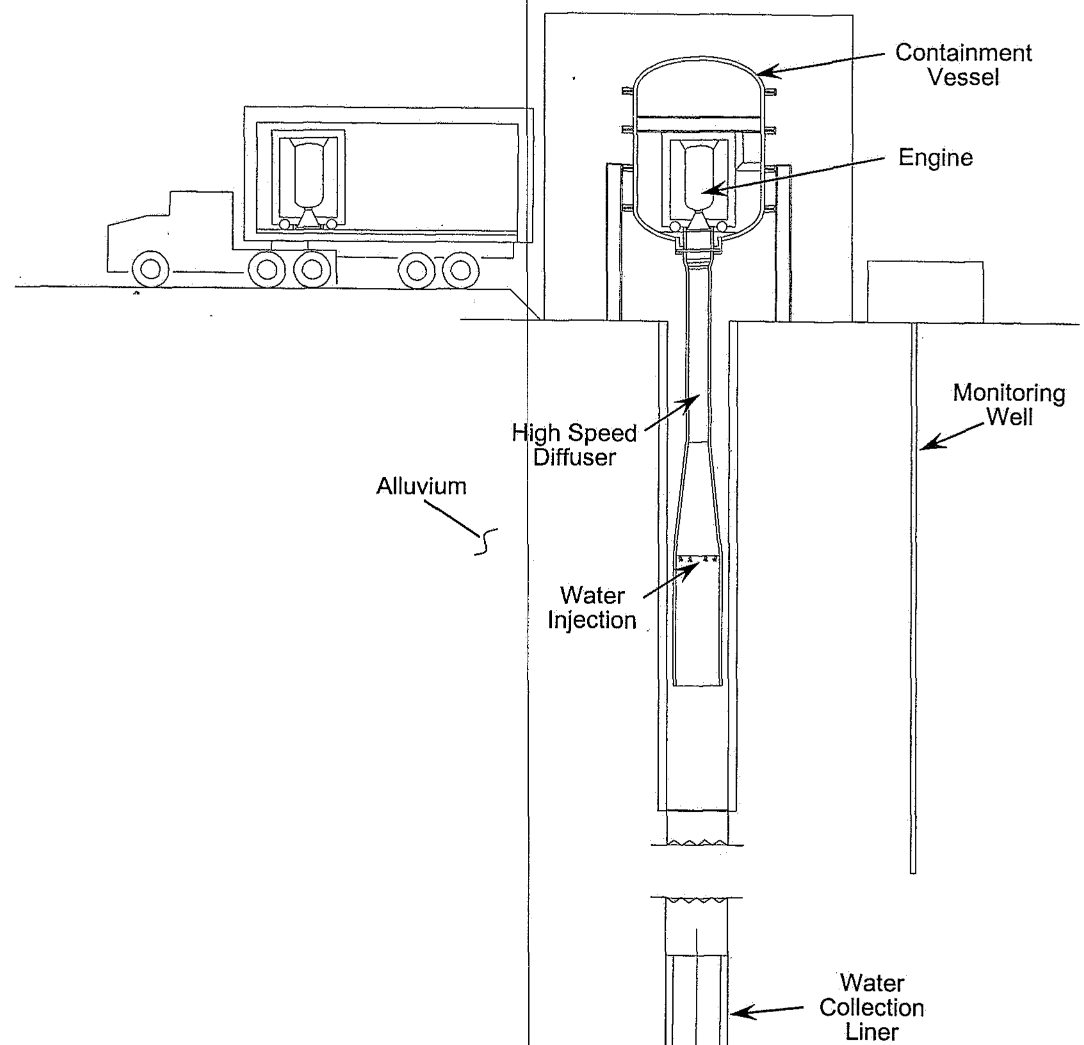
DOE Sites Only
(Ground Rule 3 Applies)



A NTP Test Facility Concept



Bore Hole Test Facility



Non-Nuclear Environmental Simulator (NTREES)

Task Manager: Bill Emrich

NASA / MSFC / ER24

NTREES Overview

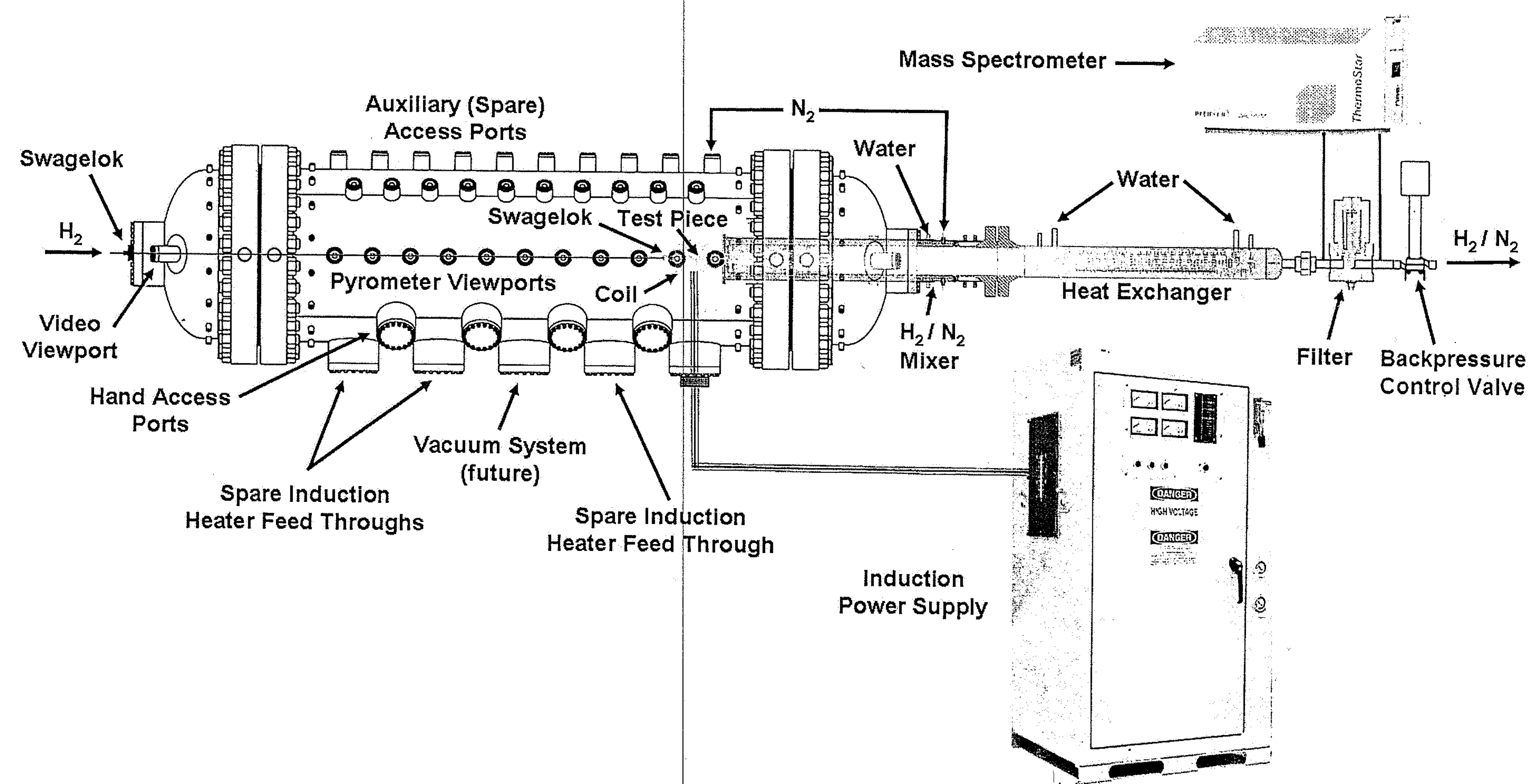
Description

- The NTREES is designed to mimic the conditions (minus the radiation) to which nuclear rocket fuel elements and other components would be subjected to during reactor operation.
- The NTREES consists of a water cooled ASME code stamped pressure vessel and its associated instrumentation coupled with inductive heaters to simulate the fission process.
- The NTREES has been designed to allow hydrogen gas to be injected into test articles mounted in the chamber.
- Numerous laboratory modifications in 4205/110 have also been required to support the operation of NTREES. These modifications include the installation of a cooling water system, a power distribution system consisting of switch panels and transformers, and a propellant gas feed/exhaust system.

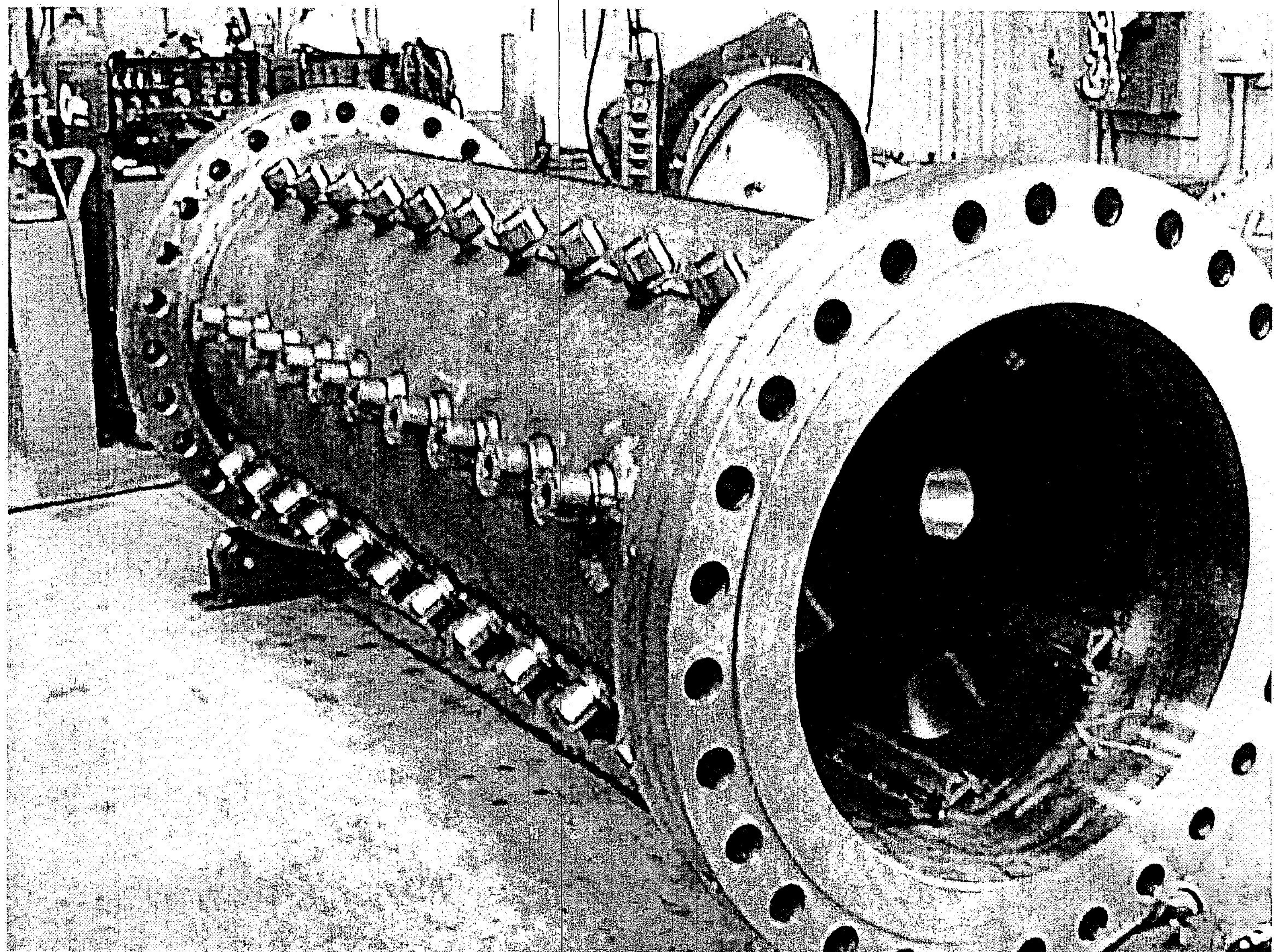
Objectives

- To test various fuel forms and materials in terms of their suitability for use in NTR engines with regard to their corrosion resistance and ultimate temperature performance.
- To investigate the operational and performance characteristics of various NTR fuel element configurations
- To develop in-house talent, capabilities, and facilities for future NTR development

NTREES System Schematic



The NTREES Chamber



NTREES Testing Approach

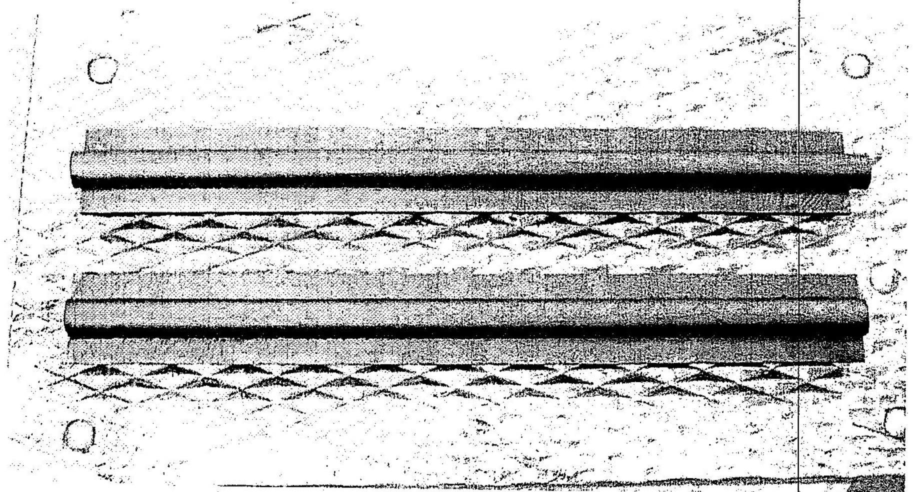
- The initial tests will use a simple graphite tube to exercise the various NTREES subsystems. The first tests will verify the operation of the flow control and water systems with the induction heater turned off. The tests will establish the operational characteristics of NTREES at several different system pressures

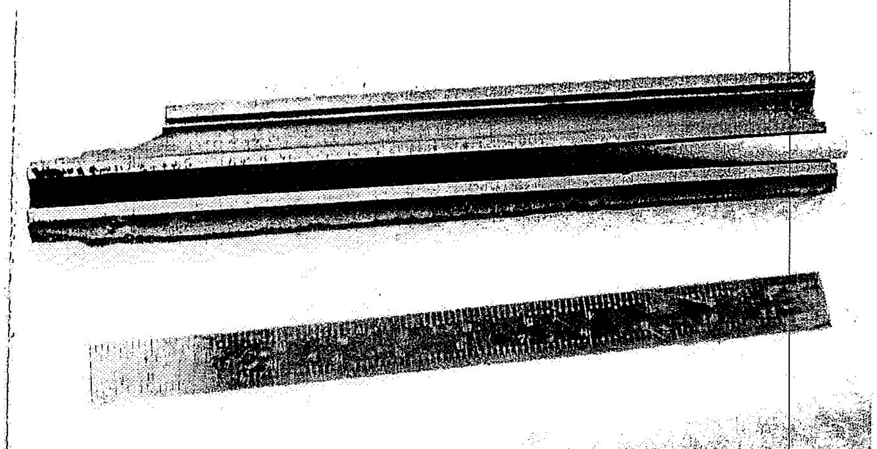
- Later tests will performed using the graphite tube with the induction heat turned on. These tests will verify the operation of the induction heater, the pyrometers, and the mass spectrometer.

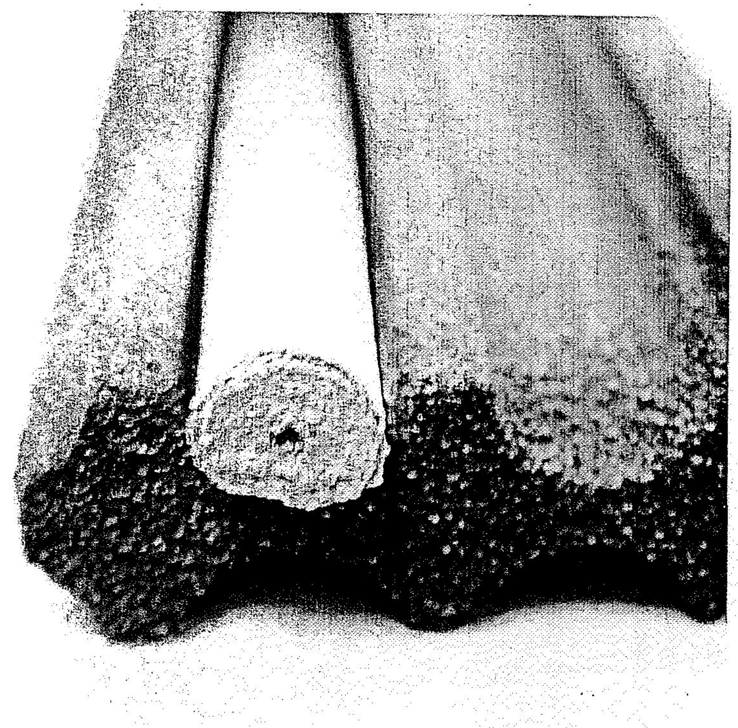
- Once the operation of all the NTREES systems have been verified, tests will be performed on ½” x 12” tubes containing depleted uranium (DU)

- It is anticipated that testing will also be conducted on 3 cermet tubes and 3 composite tubes

Depleted Uranium Test Articles







Non-Nuclear Materials Fabrication & Evaluation

Task Manager: Robert Hickman

NASA / MSFC / EM30

Task Objectives / Scope

- Objective is to evaluate fuel element materials and processes
  - Fabricability of fuel elements is a major concern
  - Fuel composition/form stability following thermal cycling and hot H_2 exposure must be investigated early to prove feasibility of designs
- Materials, processing, and properties are not well known
  - Formulation unknown
  - Processing is difficult
  - Properties depend on formulation and processing
- Develop conventional powder metallurgy (PM) processing techniques
  - Press/sinter
  - Cold Isostatic Pressing (CIP)
  - Hot Isostatic Pressing (HIP)
- Setup laboratory at MSFC for processing of NTP materials
  - Develop cermet and carbide materials and processes
  - Fabricate materials/components for characterization and hot H_2 testing

Development Approach

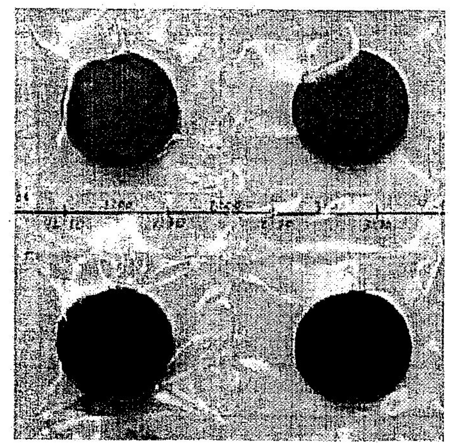
- Start with lessons learned from previous work
  - Rover/NERVA, GE710, ANL, UF/INSPI, Russia
- Materials fabrication development and characterization
  - Investigate forming/joining methods with emphasis on near net shape
  - Characterize compositions, phases, microstructure, etc.
  - Determine chemical compatibility/stability in hot H_2
  - Determine thermodynamics and diffusion phenomena
- Optimize processing and fabricate test samples
- Primary focus on prismatic cermet and graphite materials and processes
- *Non-Nuclear testing of prototypical single elements (MSFC PRL)*
  Nuclear Thermal Rocket Element Environmental Simulator (NTREES)

Development Approach (Cont'd)

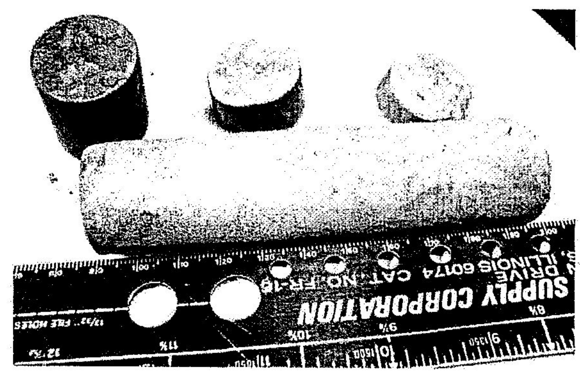
- Team/Partners
  - NASA MSFC Materials and Processes Laboratory
  - University of Florida (UF), Innovative Nuclear Space Power and Propulsion Institute (INSPI)
  - Los Alamos National Laboratory (LANL)
- Facilities/Tools
  - NASA MSFC Materials and Processes Laboratory
    - Processing and characterization
  - LANL, UF
    - Processing, testing, and machining

Surrogate Cermet Processing Trials

- Investigated PM processing such as CIP, sinter, HIP
  - Surrogate samples for planned Arc-Jet testing
  - ZrN and HfN surrogate materials for UN/UO2
  - W and W-Re matrix
- Pressed/sintered Cermets
  - Most common processing technique
  - Sintered density very dependant on powder characteristics
- Evaluated small axially pressed disc samples
  - Sintering time, temp, atmosphere (H_2, N_2)
  - Investigated powder size, morphology, purity, particle loading (20-60 volume %)
- CIP required for larger rod and tube sections
- High temp/time sinter cycles required for high density
  - Max densities of 85-93% of theoretical
  - Density is key factor in fuel loss/stability



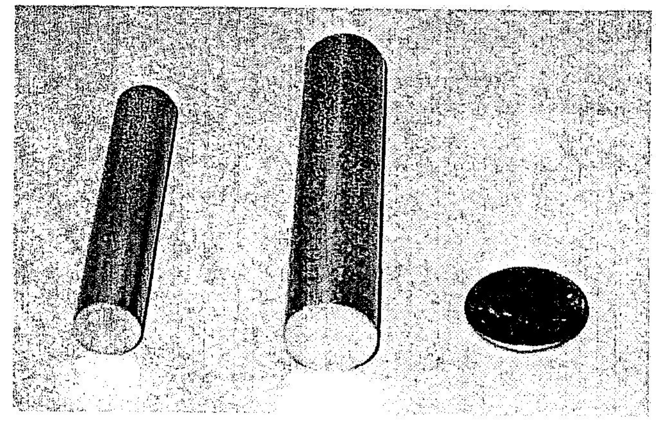
Press/Sintered W-3Re/ZrN
(20, 40, 60 vol% ZrN)



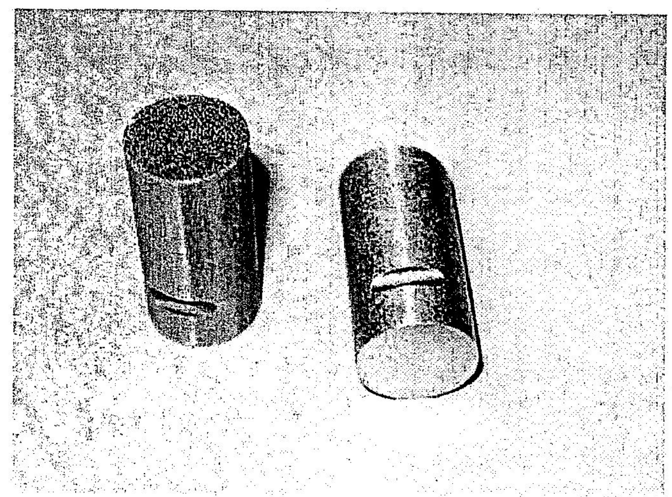
CIP'ed W-3Re/ZrN
(60 vol% ZrN)

Surrogate Cermet Processing Trials

- Developed Hot Isostatic Pressing (HIP) techniques for Cermets and Carbides
  - Demonstrated for W-5Re/40 volume % HfN
  - Near theoretical densities (>99% dense)
  - Not as sensitive to powder characteristics
- Evaluating HfN and W particle size effects on microstructure
  - Particle distribution
  - Particle clustering and agglomeration
  - Particle bonding
  - HfN particles sizes from 5-150 microns
- Currently investigating HIP techniques to fabricate near net shape elements
  - Single and multi-channel tubes
  - Integral HIP bonded W-Re claddings



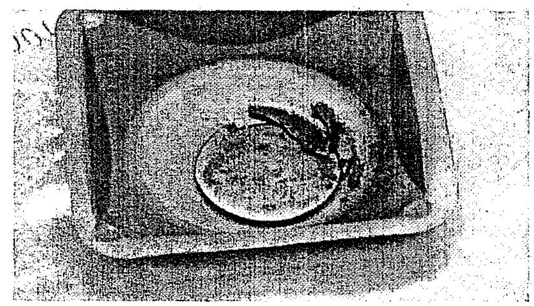
W-5Re/40 volume % HfN Cermets



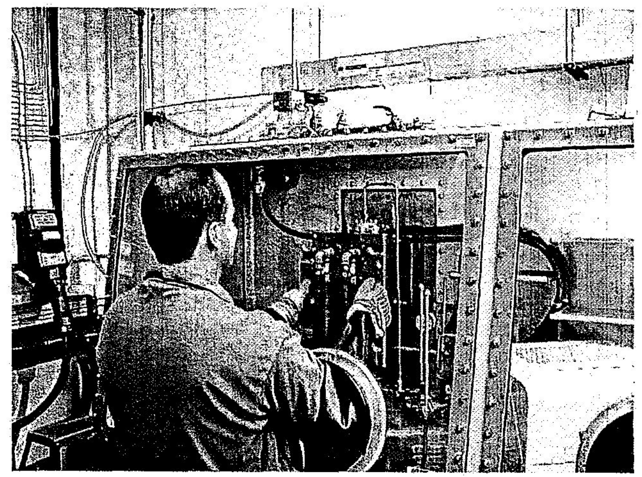
W-5Re/40 volume % HfN Cermet Samples for Hot H2 Arc-Jet Testing

Fabrication of Depleted UN at LANL

- LANL contracted to fabricate UN powders
  - Processing based on SP100/JIMO heritage
- Leveraged existing LANL equipment/facilities to setup new fabrication line
  - Glovebox
  - High temperature furnace
  - Powder pressing, milling, and sieving
- 1-kg of depleted UN delivered to MSFC for testing
- Chemistry, phases and particle size data to be provided by LANL



Surrogate ZrN Powders



Surrogate ZrN Samples being loaded into Glovebox and Integral Furnace

Cermet Development and Test Plan

- 2nd iteration of HIP processing for surrogates is currently in progress
  - Processes are being optimized for fabrication of DU-based cermet samples
- Fabricate DU-based cermets for Hot H2 testing
  - Investigate composition, density, and microstructure effects on fuel loss and stability

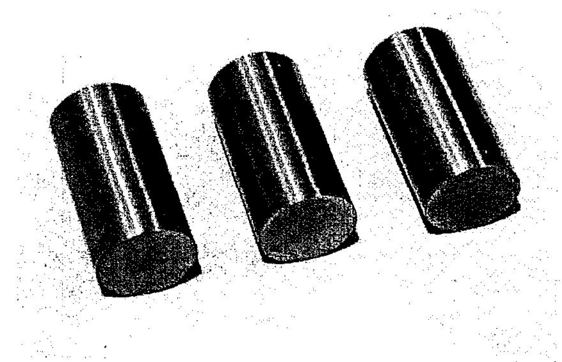
Notional Cermet Sample Test Matrix

Process	Materials	Shape	Size / Test
HIP	*W-Re/UN	Rod or Disc	TBD / Furnace (cyclic and long term)
HIP	*W-Re/UO2 (stabilized?)	Rod or Disc	TBD / Furnace (cyclic and long term)
HIP	W/UN	Rod or Disc	TBD / Furnace (cyclic and long term)
HIP	W/UO2 (stabilized?)	Rod or Disc	TBD / Furnace (cyclic and long term)
Press/Sinter	*W-Re/UN	Rod or Disc	TBD / Furnace (cyclic and long term)
Press/Sinter	*W-Re/UO2 (stabilized?)	Rod or Disc	TBD / Furnace (cyclic and long term)
Press/Sinter	W/UN	Rod or Disc	TBD / Furnace (cyclic and long term)
Press/Sinter	W/UO2 (stabilized?)	Rod or Disc	TBD / Furnace (cyclic and long term)
HIP	W-5Re/UN	Tube	0.5" OD x 0.1" ID x 12" Long / NTREES
HIP	W-5Re/UO2 (stabilized?)	Tube	0.5" OD x 0.1" ID x 12" Long / NTREES

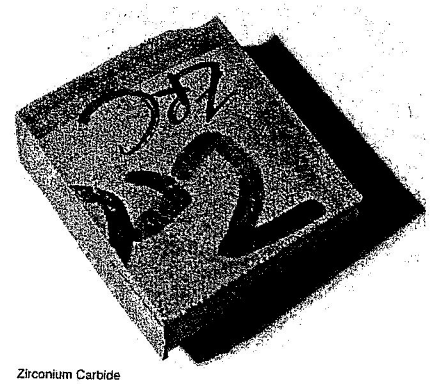
*Rhenium additions will likely be varied from 5-25% by weight

Surrogate Carbide Processing Trials

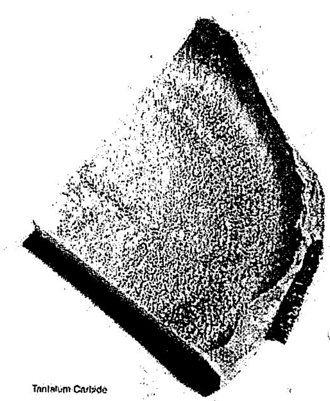
- Press/sinter and HIP processes demonstrated for single carbides such as ZrC, TaC, etc.
- NbC/ZrC and other mixed carbides currently being fabricated
- LANL contracted to fabricate UC powder (5 kg)
- Tri-carbide materials are planned for in-house fabrication



Machined Carbide Samples for Arc-Jet Testing at MSFC



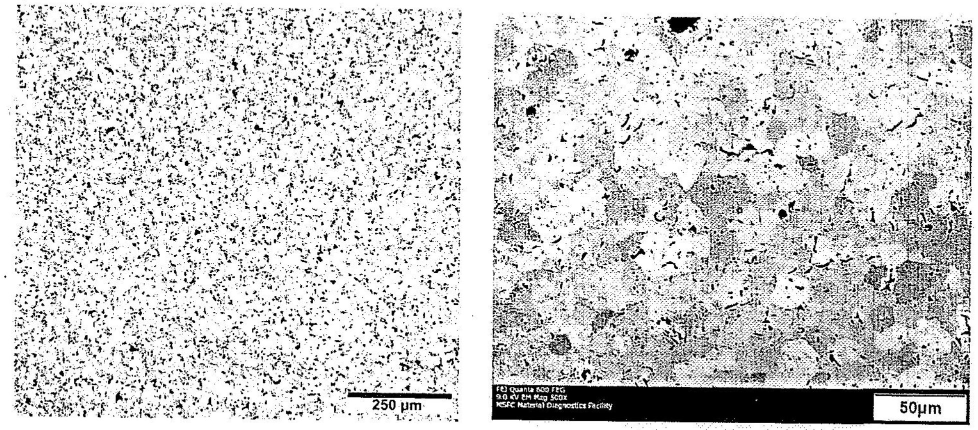
HIP'ed ZrC



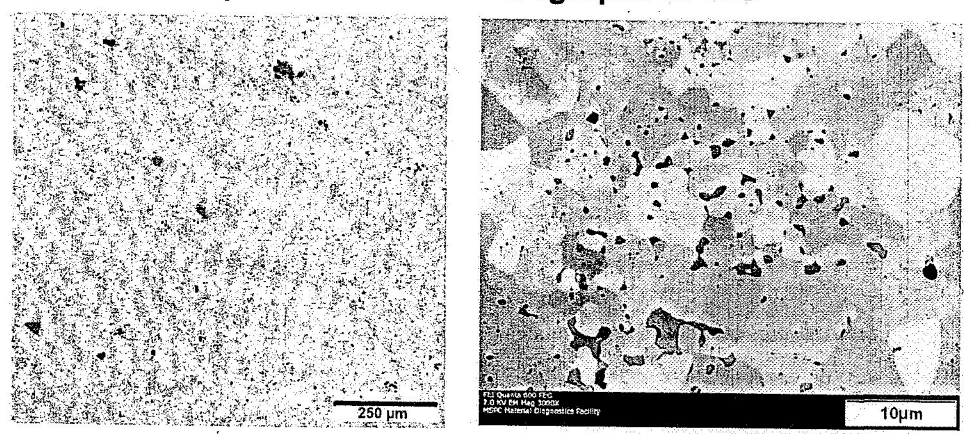
HIP'ed TaC

Surrogate Carbide Characterization

- Characterization of carbide and cermet materials performed at MSFC Materials and Processing Lab
  - Optical and SEM microscopy
  - Hardness, chemistry, phases, etc
- Single Carbides
  - Fine grained and high density
  - Some evidence of free carbon and oxy-carbide phases



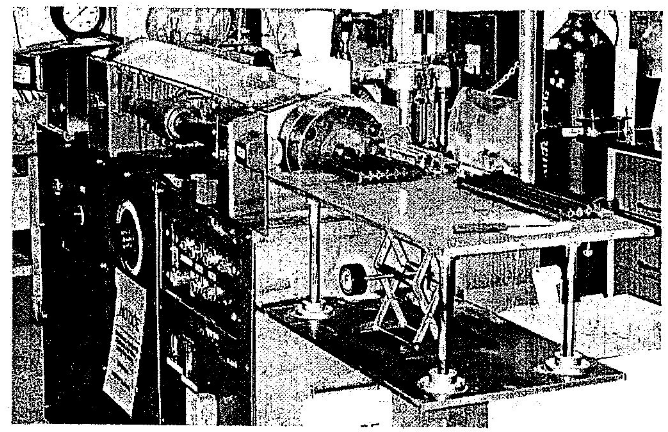
Optical and SEM Micrographs of ZrC



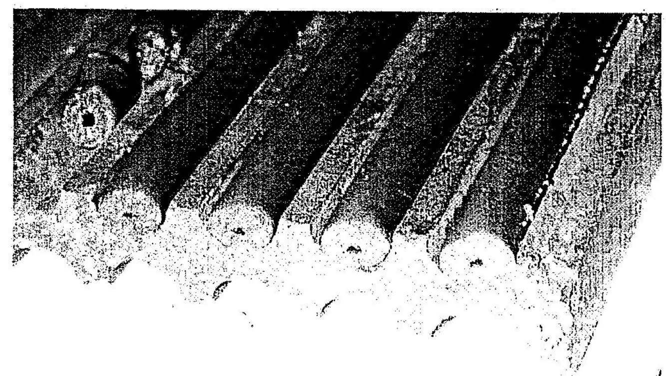
Optical and SEM Micrographs of TaC

(U, Zr)C-Graphite Composites at LANL

- LANL fabricating (U,Zr)C-graphite composite tubes
  - Rover/NERVA heritage
  - Interconnected (U,Zr)C phase in graphite matrix
- Rover legacy materials and hardware
  - Blend and grind materials, extrude, cure, bake, low fire, high fire (up to 3100K), and machine
  - CVD ZrC coating on ID
- Facility upgrades and processing trials
  - Tube furnaces for 200C, 400C, 800C curing and bake out steps set up in the Rad Control Area
  - Dies/tooling re-designed and fabricated
  - HfO_2-ZrC-graphite mix used as surrogate for blending and extrusion trials
  - Setup of the CVD apparatus has begun
- Six (6) tubes to be delivered ready for testing in MSFC hot hydrogen facility
  - Four (4) ZrC coated, Two (2) uncoated



Laboratory Extrusion Press



End View of Extruded Surrogate Graphite Composite Tubes

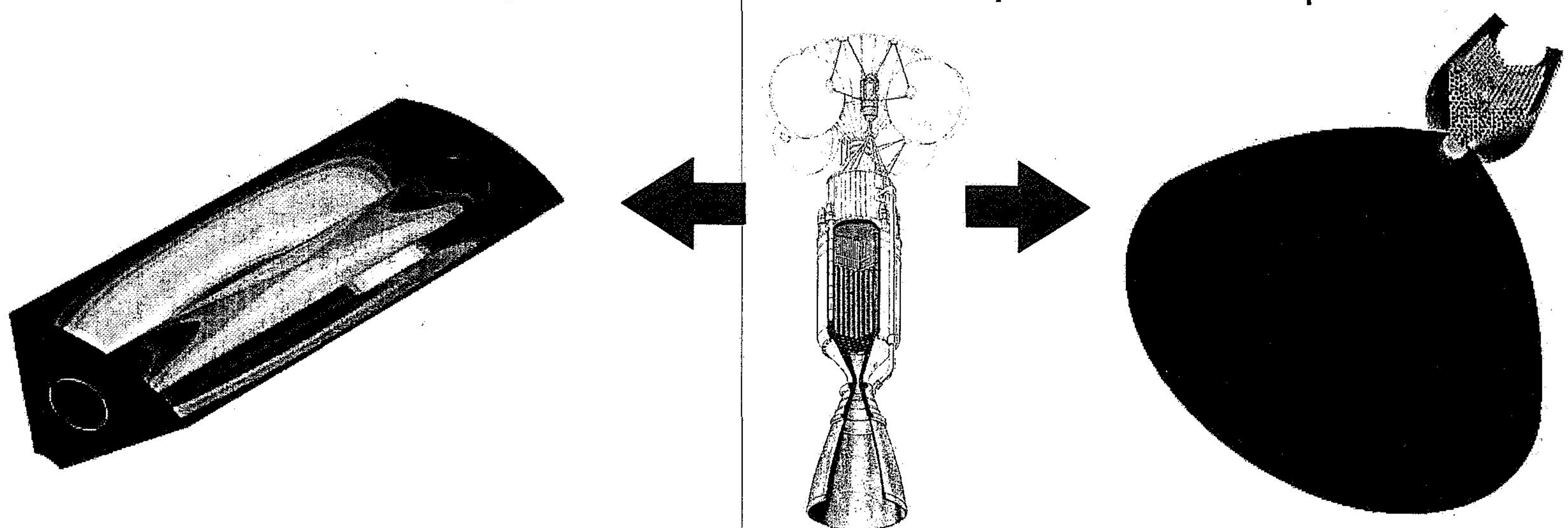
Multi-Physics TCA Modeling

Task Manager: Ten-See Wang

NASA / MSFC / ER43

Description

- **Objective**
  - Develop an efficient and accurate thermo-fluid computational model based on an existing CFD code UNIC to predict environments for solid-core nuclear thermal engine thrust chamber design and analysis
- **Scope**
  - A NERVA-type engine (Small Engine) design of flow element and thrust chamber will be analyzed
  - Ties closely with other MSFC Tasks (7, 12, and 13) and an IR&D project entitled "Hot Hydrogen Materials and Component Development"



Approach

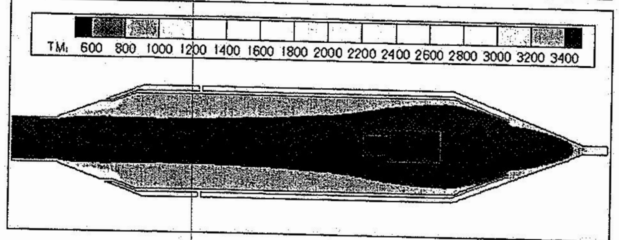
- **Subtasks**
  - UNIC code enhancement and benchmarks
  - Axisymmetric single-channel flow element
  - Axisymmetric global thrust chamber
  - 3-D multi-channel single flow element
  - 3-D global thrust chamber analysis
- **Codes**
  - UNIC and SINDA (for benchmarking)
- **Facility**
  - Thermal and Combustion Analysis Branch cluster

Accomplishments

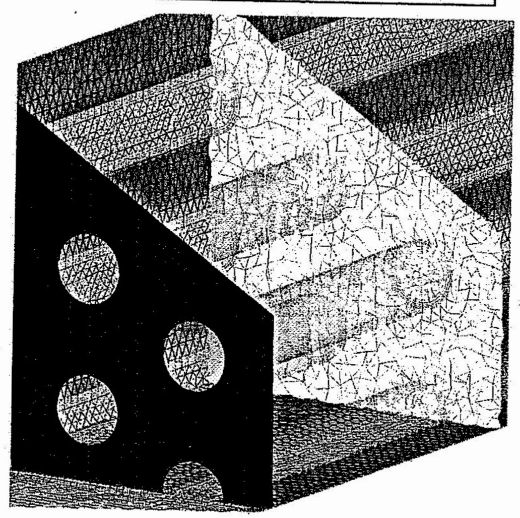
- **Created a multiphysics thermal-fluid code UNIC that predicts environments for solid-core nuclear thermal engine thrust chamber design and analysis. The multiphysics invoked in this study include turbulent heat transfer, conjugate heat transfer, power generation, variable gas and solid thermal properties, thermal radiation, and finite-rate chemistry. The enhancements made to UNIC include:**
  - Implemented conjugate heat transfer for gas/solid and gas/solid/porous media (including temporal gas-solid interface formulation)
  - Implemented options to run variable thermal properties for solids and porous media
  - Implemented power generation module to run 2 types of profiles
    - Cosine profile
    - Arbitrary profile
  - Implemented a multi-step power ramping procedure to change power level during execution

Accomplishments

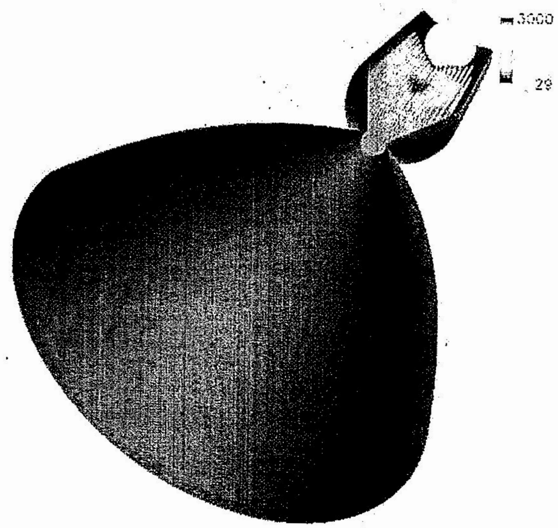
1. Benchmark and predictions on cylindrical specimen heated by an impinging hot hydrogen jet



2. Detailed analysis of Multi-channel single flow element



3. Global analysis of thrust chamber



Accomplishments

- **Benchmark analyses and predictions on conjugate heat transfer of cylindrical specimen heated by an impinging hot hydrogen jet (from arc heater)**
  - Benchmarked steady-state solutions with those of SINDA
  - Completed steady-state predictions with variable (U,Zr)C-graphite composite properties
  - Completed transient predictions with variable (U,Zr)C-graphite composite properties
- **Detailed analysis of multi-channel single flow element**
  - Completed a powered pseudo-7-channel single flow element analysis
  - Analyses of (Small Engine) 19-channel single flow element
    - Un-powered case for porosity modeling
    - Powered case to provide environments for failure analyses
- **Global analysis of thrust chamber**
  - Completed a simplified (powered) global thrust chamber analysis
  - Analyses of (Small Engine) powered thrust chamber

Summary

A significant body of relevant work was accomplished through the NTP tasks at NASA-MSFC. The products of these tasks has been preserved can be utilized to contribute to future nuclear propulsion and power efforts.

Requests for further information regarding these tasks should communicated to:

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